Institute of Production Engineering and Photonic Technologies

Hazardous laser sources…

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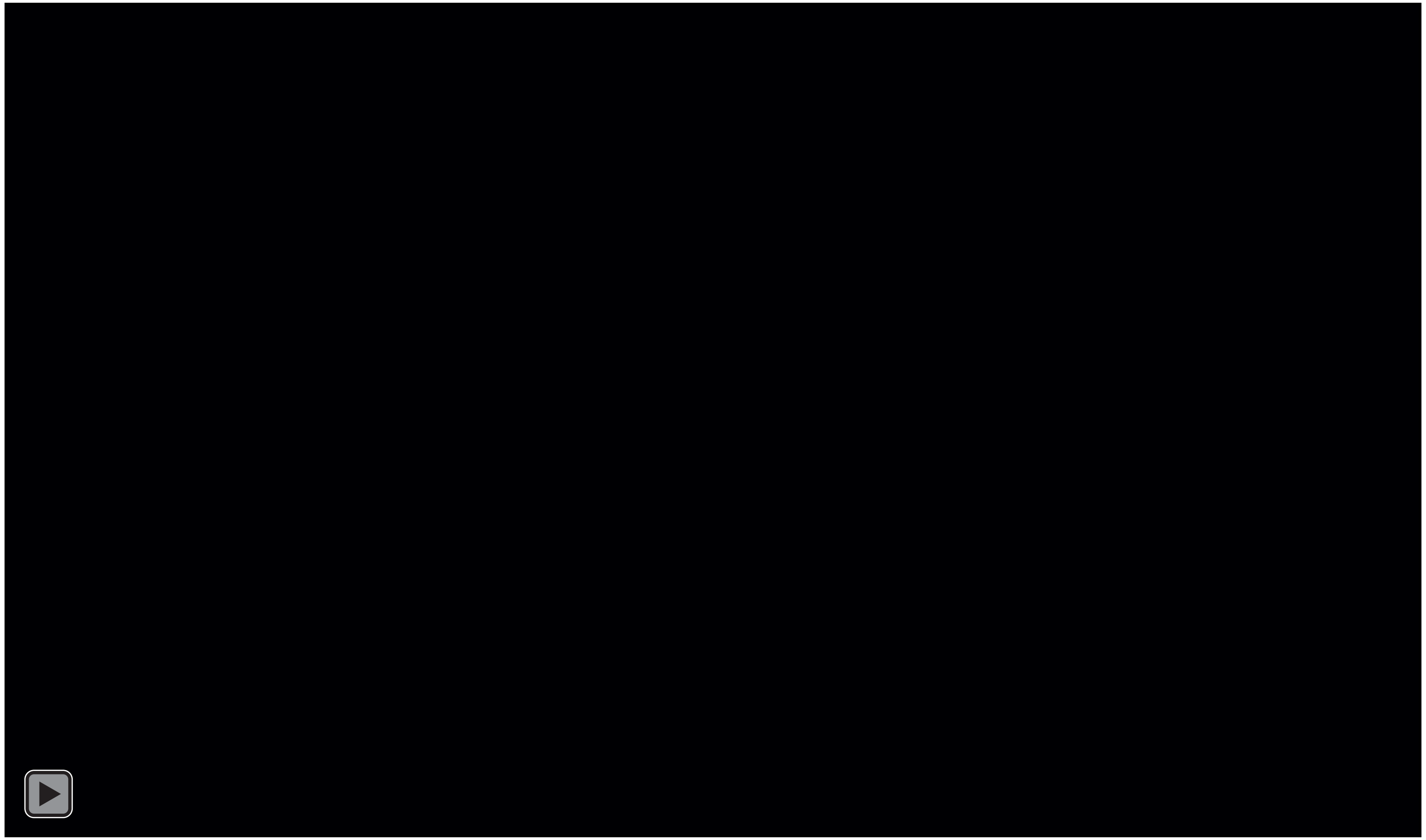
Available laser sources

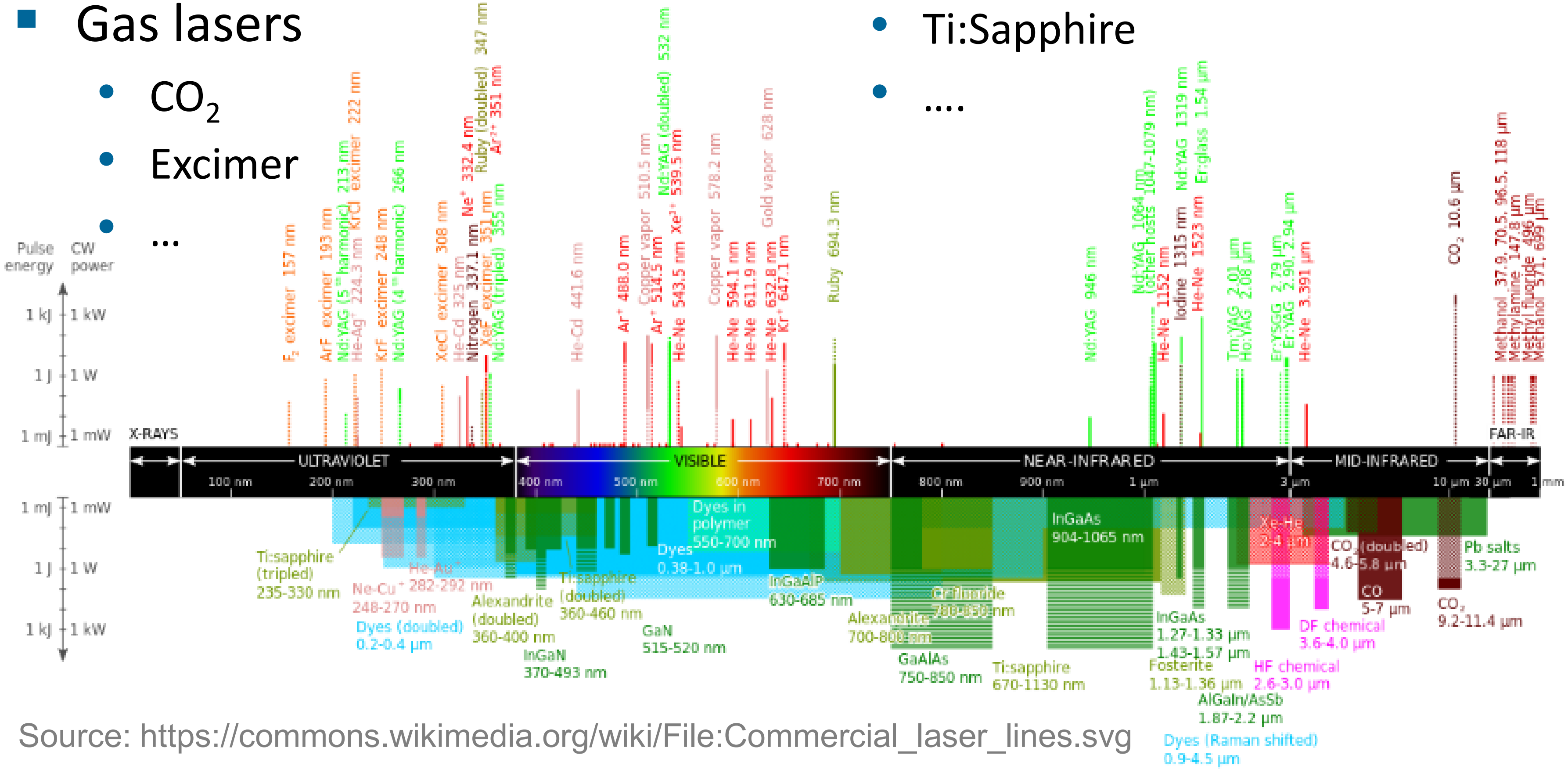
- Laser sources and measurement devices
  - 1.5 kW fiber laser with 100 µm fiber - to be replaced in the near future
  - 1.5 kW cutting laser
  - 300 W diode laser
  - 25 W excimer laser
  - 1 kW diode laser, integrated in forming tools
  - Ultrafast laser (< 30 fs) Multi-Pass-Amplifier (0.8 mJ pulse energy, 1 kHz rep rate)
  - Ultrafast laser (approx. 220 fs), 5 W, SHG and THG output, cooperation with SME
  - Optical contact angle goniometer
  - 3D surface measurement devices
  - Light microscopes and SEM
  - …

High power laser sources: Are they really dangerous?



Laser types:

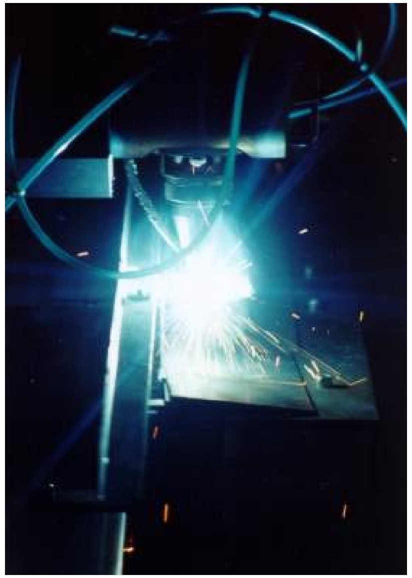
- Dye lasers
  - Organic dye in liquid solution
  - Short pulses, high pulse energies
- Gas lasers
  - CO_2
  - Excimer
  - …
- Semiconductor lasers
- Solid state lasers
  - Nd:YAG, Yb:YAG, Yb-Glass, ….
  - Ti:Sapphire
  - ….

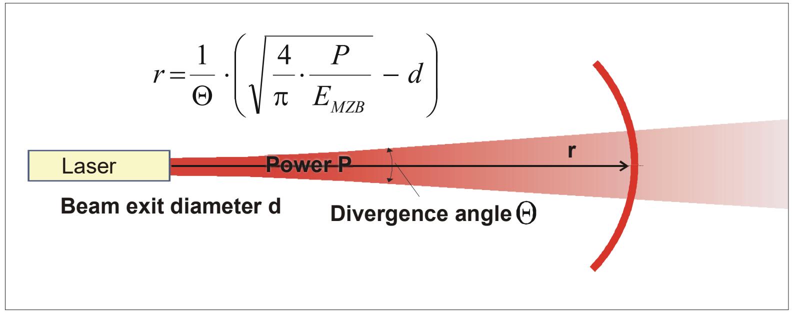


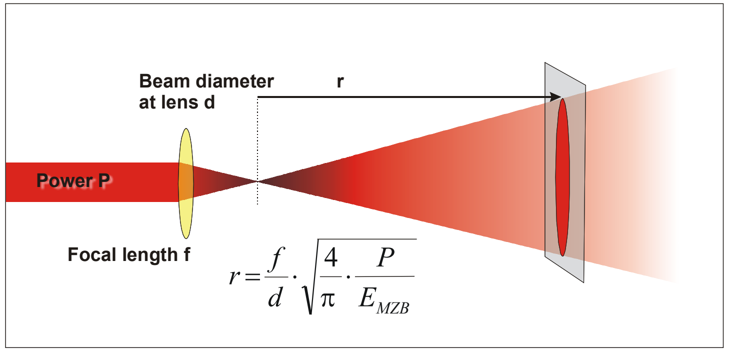
Source: https://commons.wikimedia.org/wiki/File:Commercial_laser_lines.svg

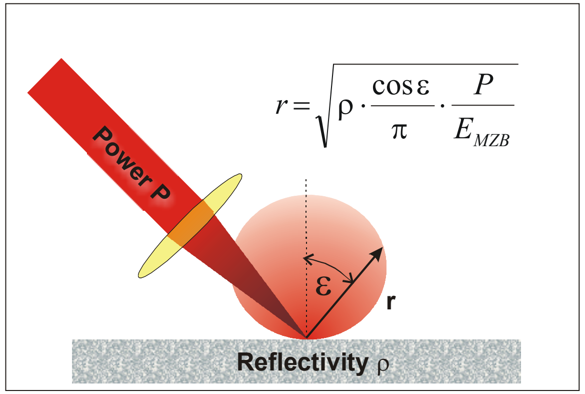
High power laser sources: possible hazards

Source	Hazards
Laser radiation	Raw beam, reflected, scattered radiation Secondary radiation,…
Reaction products	Vapour, fumes, (very) small particles, toxic gases,…
Processing station	Moving parts, high voltage, toxic gases,…

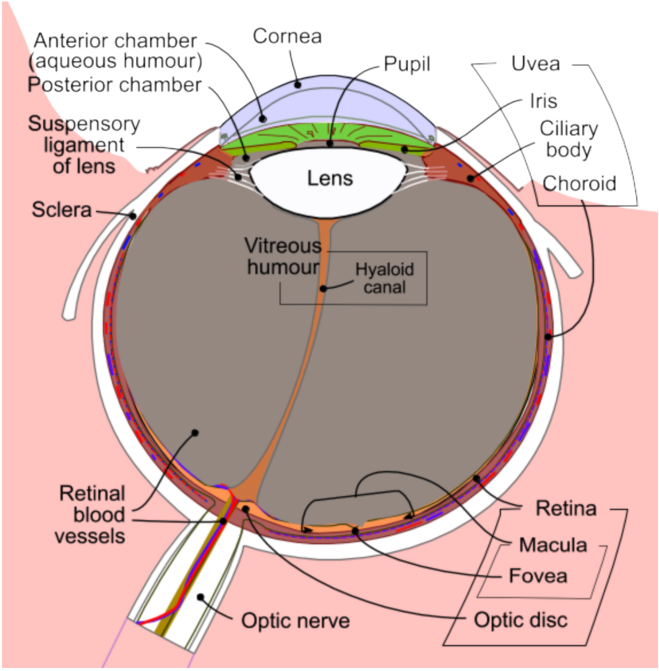








High power laser sources: possible hazards



Source: https://commons.wikimedia.org/wiki/File:Schematic_diagram_of_the_human_eye_en.svg#/media/File:Schematic_diagram_of_the_human_eye_en.svg

Wavelength range	Pathological effect
180–315 nm (UV-B, UV-C)	Photokeratitis (inflammation of the cornea, equivalent to sunburn), accumulating damage
315–400 nm (UV-A)	Photochemical cataract (clouding of the eye lens)
400–780 nm (visible)	Photochemical damage to the retina, retinal burn
780–1400 nm (near-IR)	Cataract, retinal burn
1.4-3.0 µm (IR)	cataract, corneal burn,…
3.0 µm–1 mm	Corneal burn

Skin is usually much less sensitive.

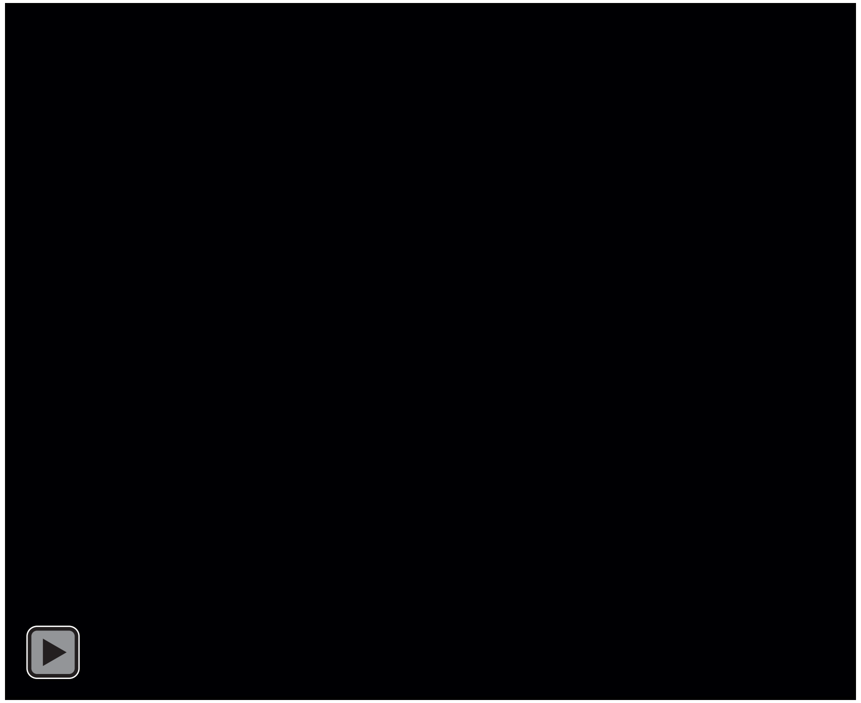
High power laser sources: possible hazards

- CO_2-Lasers (λ=10.6µm):
  - Direct and directly reflected beam dangerous
  - Diffuse reflections usually not dangerous (depends on the distance)
  - Plasma in deep penetration welding emits UV- and blue-radiation, protection necessary.

Source: Coherent

- Solid state lasers (fiber, YAG,…) $\lambda\approx$1.0….µm)
  - Direct, reflected beam as well as scattered radiation are focused on eye‘s retina, <u>very dangerous</u> (always use goggles or protective housing !!)
  - Plasma in deep pentration welding emits only a low amount of UV-radiation, protection ususally not necessary.

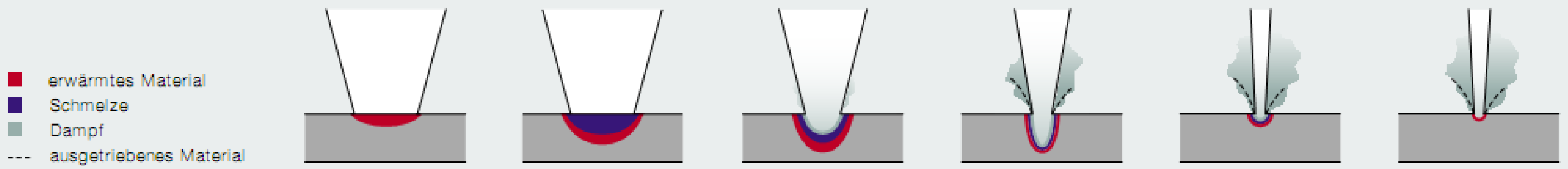
High power laser sources: possible hazards



Source: Coherent

- Diode-Lasers (λ≈ VIS…IR)
  - Comparable to solid state lasers
- Excimer lasers (λ≈126nm … 351nm)
  - Uses toxic gas under high pressure (fluorine, chlorine). Protective enclosing with exhaust system
  - UV-radiation shows an accumulating effect. Even low exposure rates are dangerous.

Pulse duration and interaction mechanisms

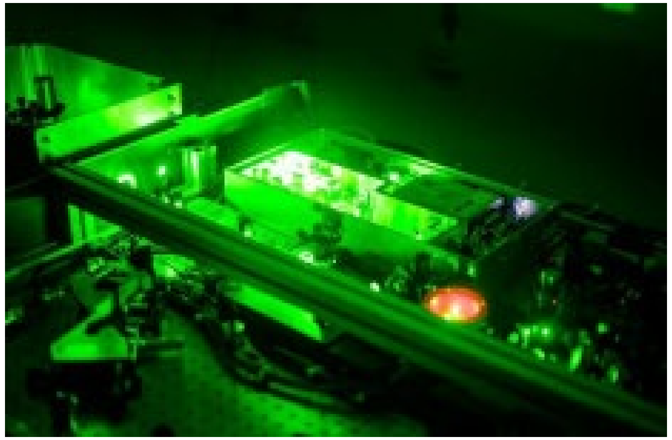


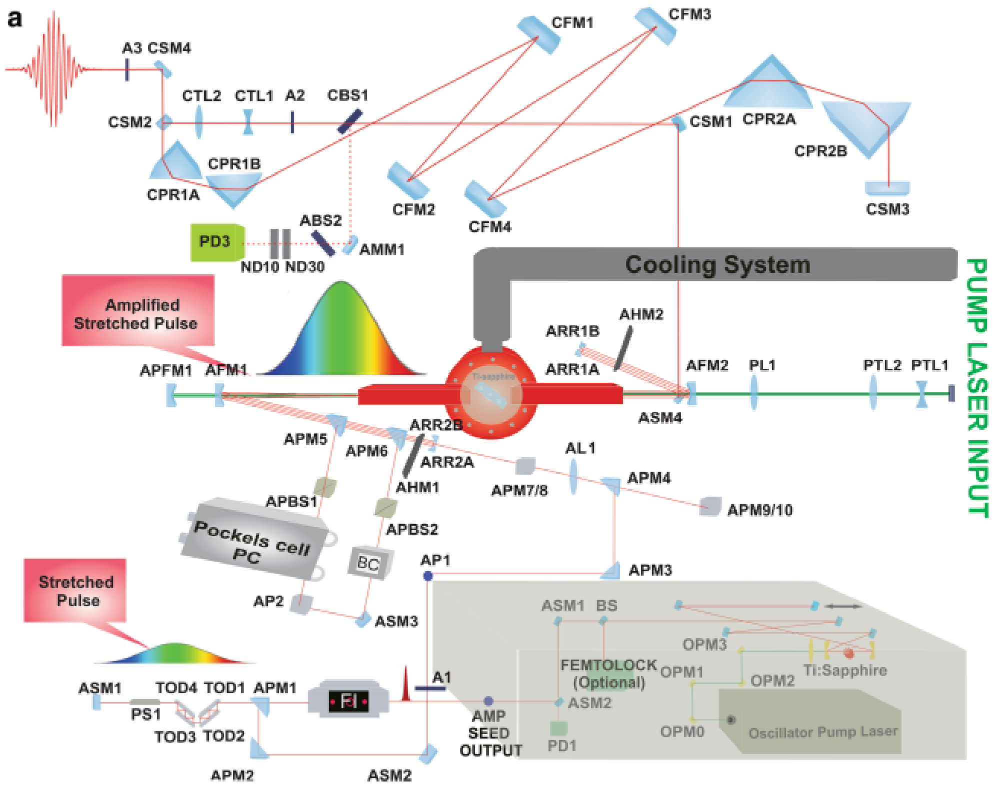
Hauptwirkung	Erwärmen	Schmelzen	Schmelzen und Verdampfen	Verdampfen	Verdampfen und Ionisieren	Sublimieren und direkte Dissoziation
Leistungsdichte ab	30 W/mm²	1 kW/mm²	10 kW/mm²	1 MW/mm²	10 MW/mm²	10 GW/mm²
Einwirkzeit	s	ms	ms	ms	ns	ps
Verfahrensbeispiele	Härten, Löten	Wärmeleitungsschweißen	Tiefschweißen, Schneiden	Bohren	Abtragen, Gravieren	Strukturieren

Source: Trumpf

Very short laser pulses - Ti:Sapphire laser

- Ultrafast laser → fs pulses
- 30 fs pulse: light travels approx. 10 µm, bandwidth ~100 nm
- Non-linear interaction mechanisms

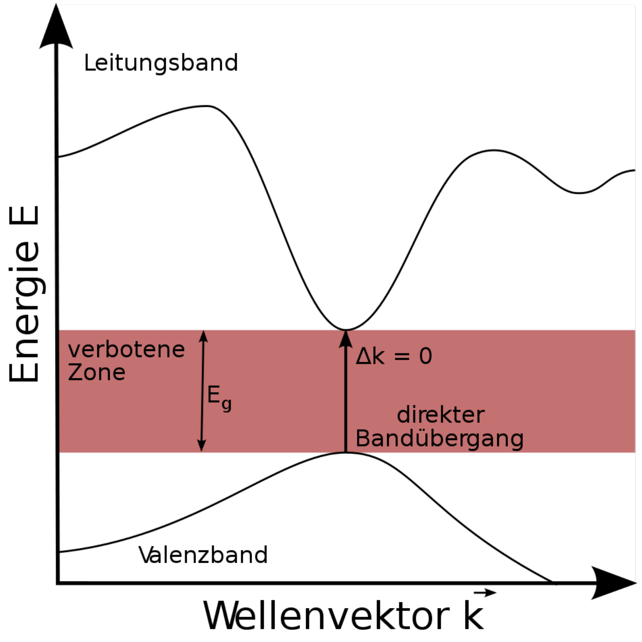




Non-conducting materials (insulator, semiconductors): Between conduction band and valence band: band gap with a certain energy E_g.

Band gap energy E_g approx 0,7 eV (Ge) – several eV

Insulator = large band gap, at very high field strength electrons are shifted from the valence band to the conduction band: breakdown

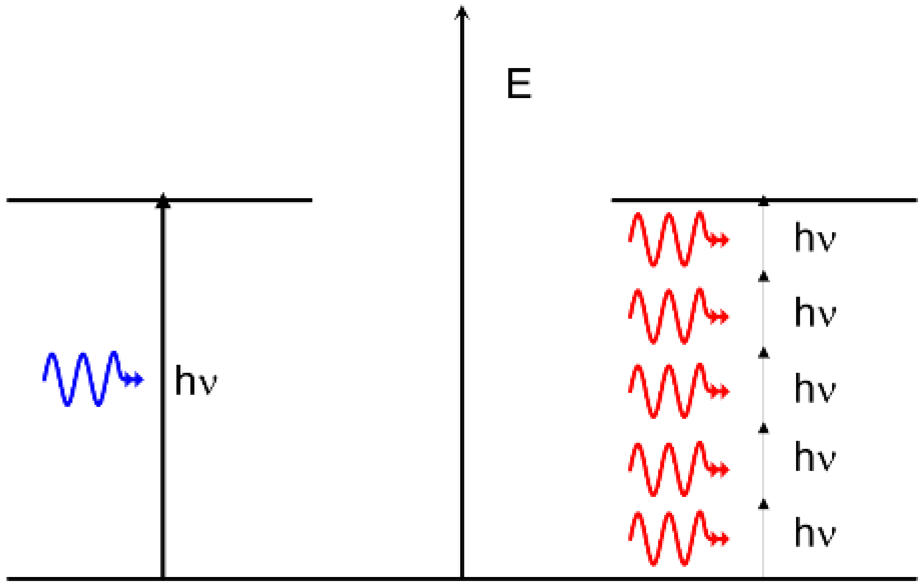


Source: wikipedia

With extremely short pulses, many photons hit the atom in a very short period of time: multiphoton absorption

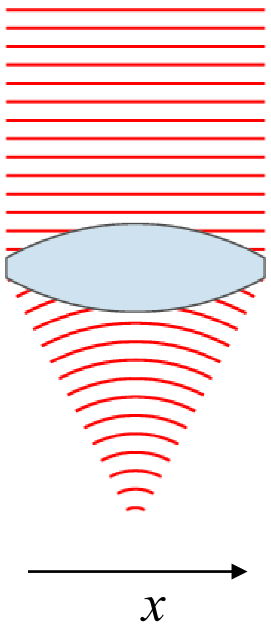
Free electrons suffer from collisions among each other → multiplication by „inverse Bremsstrahlung“ and additional collisions

Insulator behaves like a conducting material



Non-linear effects due intense electromagnetic radiation

A lens is a lens because the phase delay seen by a beam varies with *x*



Source: wikipedia

Intensity dependent refractive index:
$n = n_0 + n_2 I(x,t)$ leads to self-focusing of an intense, gaussian laser beam

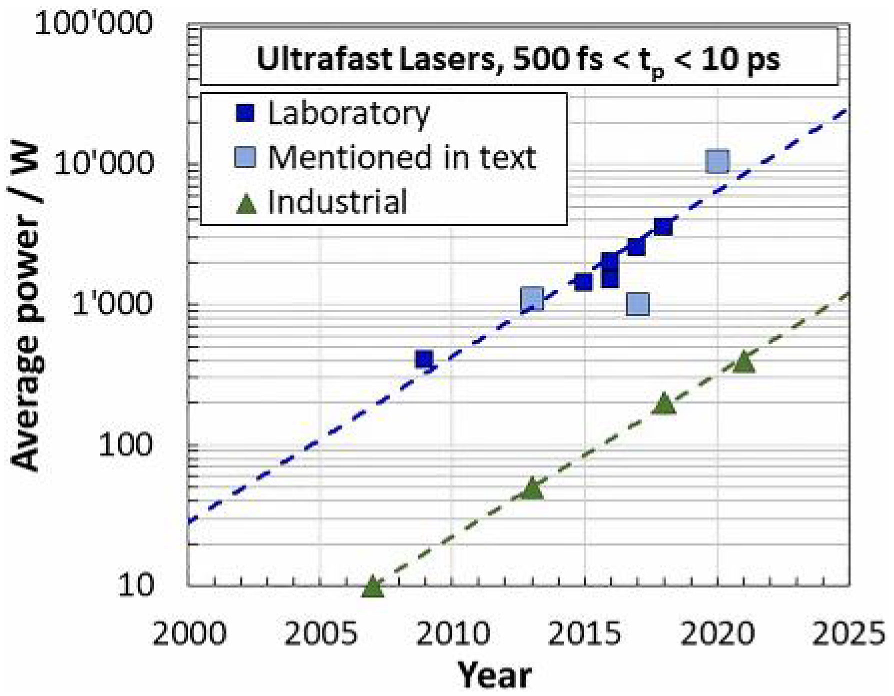
Material	n_0	n_2 [cm^2/W]
Air	~1	~5E-19
Quarz	~1.5	~3E-16

$$P_{cr} \approx \frac{3.77 \cdot \lambda^2}{8\pi n_0 n_2}$$

For radiation with a wavelength of 800 nm: $P_{cr} \approx 2\,GW$

Ultrafast lasers

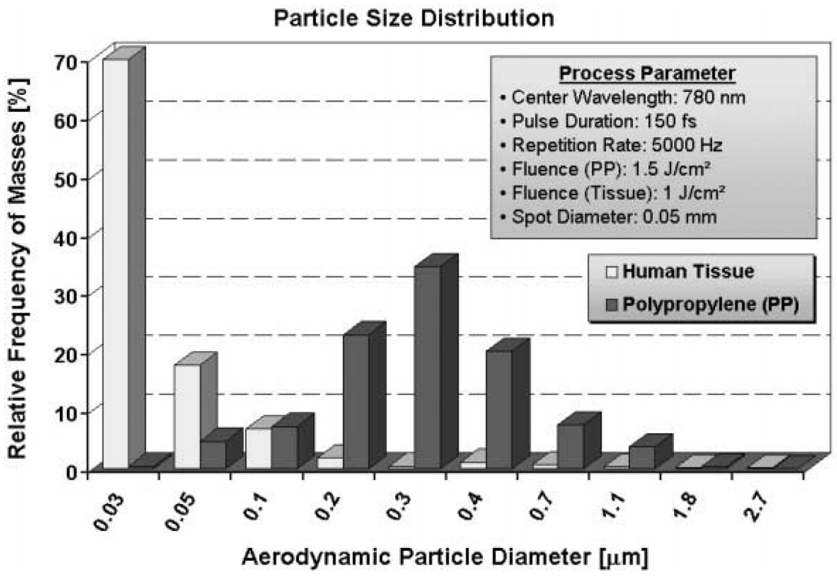
- Pulse energies up to ~mJ
- Average power ~kW
- Irradiance up to ~10^{15} W/cm^2
- Generation of free electrons by the leading edge of the laser pulse
  - Bremsstrahlung
  - Collisions
- Hot electrons
- (strong) plasma formation
- Emission of x-ray radiation
- Photon energies up to ~10eV
- X-ray emission depends on plasma development



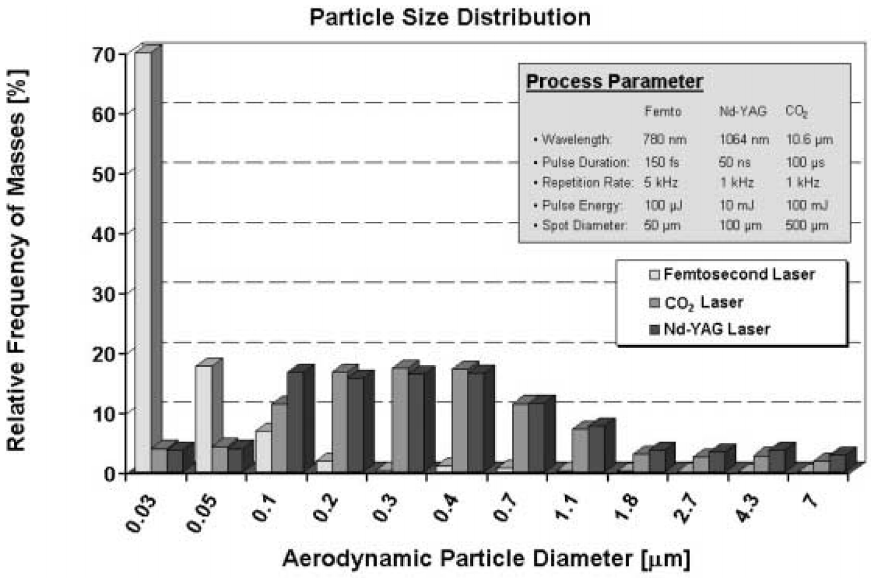
Source: Weber et al., AOT vol. 10, no.4-5, 2021, pp. 239-245.
https://doi.org/10.1515/aot-2021-0038

Ultrafast lasers – particle emissions

- Material removal by ultrashort pulses leads to particle emissions



- Size distribution depends on the irradiance



Bunte, J. et al., Topics in Applied Physics, vol 96. Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-540-39848-6_20

High power laser sources: Safety measures

Engineering	Procedure controls	Protective Equipment
Protective housing	Laser safety officer	Eyewear
Door interlocks, remote control	Operating procedures	Clothing
Beam shutter	Limitation on use by class	Gloves
Key switch	Usage limitation	
Warning lights	Education, training	
Controlled beam path	Marking of protective devices	
Laser area	Warning signs and labels	

Ultrafast lasers – summary

- Non-linear effects due to very high irradiances: self-focusing
- Strong plasma formation due to very high irradiances
- Hot electrons can be a source of x-ray radiation
- At close distances, x-ray emission doses can exceed regulatory exposure limits
- Protection measures (distance and/or steel sheets) should taken into account
- Particle emissions due to ultrafast processing
- Particle size depend on irradiance
- Larger irradiance causes smaller particles
- Ablated volume is relatively small
- Exhaust system recommended

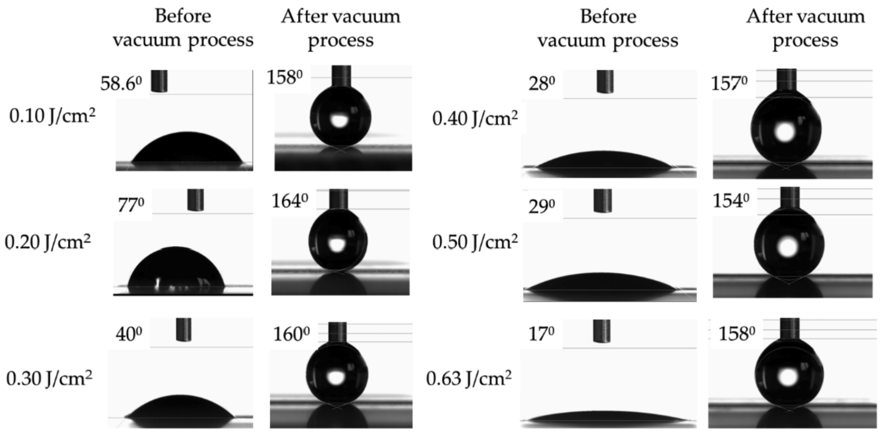
Thanks for your attention!

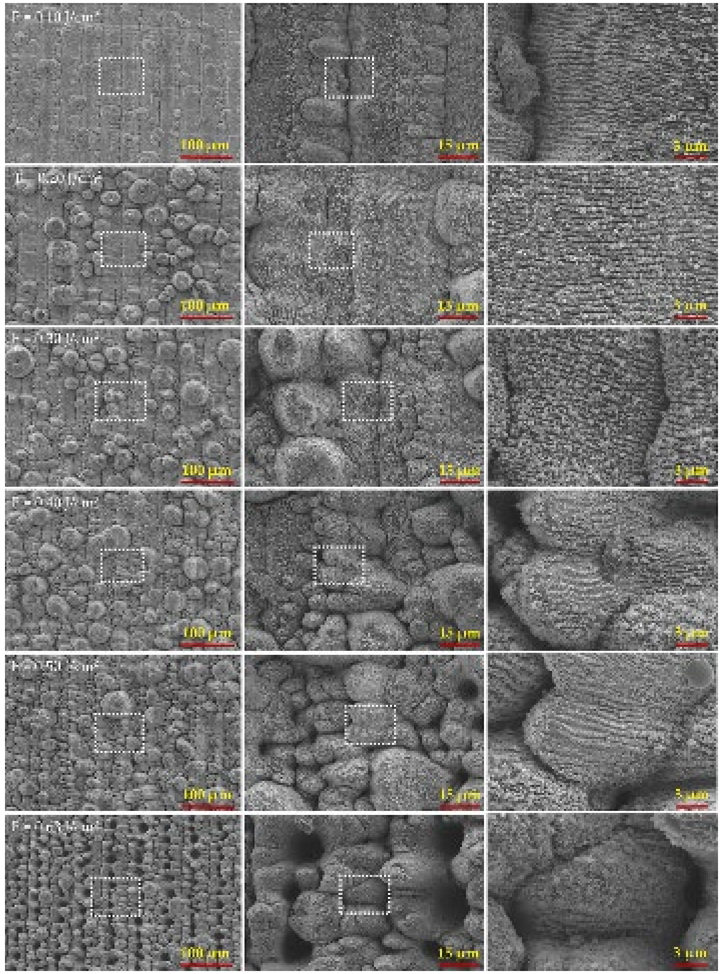
Laser safety

Safety class	Simplified description
1	The accessible laser radiation is not dangerous under reasonable conditions of use. Examples: 0.2-mW laser diode, fully enclosed 10-W Nd:YAG laser
1M	The accessible laser radiation is not hazardous, provided that no optical instruments are used, which may e.g. focus the radiation.
2	The accessible laser radiation is limited to the visible spectral range (400–700 nm) and to 1 mW accessible power. Due to the blink reflex, it is not dangerous for the eye in the case of limited exposure (up to 0.25 s). Example: some (but not all) **laser pointers**
2M	Same as class 2, but with the additional restriction that no optical instruments may be used. The power may be higher than 1 mW, but the beam diameter in accessible areas is large enough to limit the intensity to levels which are safe for short-time exposure.
3R	The accessible radiation may be dangerous for the eye, but can have at most 5 times the permissible optical power of class 2 (for visible radiation) or class 1 (for other wavelengths).
3B	The accessible radiation may be dangerous for the eye, and under special conditions also for the skin. Diffuse radiation (as e.g. scattered from the some diffuse target) should normally be harmless. Up to 500 mW is permitted in the visible spectral region. Example: 100-mW continuous-wave frequency-doubled Nd:YAG laser
4	The accessible radiation is very dangerous for the eye and for the skin. Even light from diffuse reflections may be hazardous for the eye. The radiation may cause fire or explosions. Examples: 10-W **argon ion laser**, 4-kW **thin-disk laser** in a non-encapsulated setup

Ultrafast laser processing

- Modifications of surface properties
- SCA can be modified from hydrophilic to (super)hydrophobic behaviour
- Thermal stability tests showed that superhydrophobic properties were able to withstand elevated temperatures

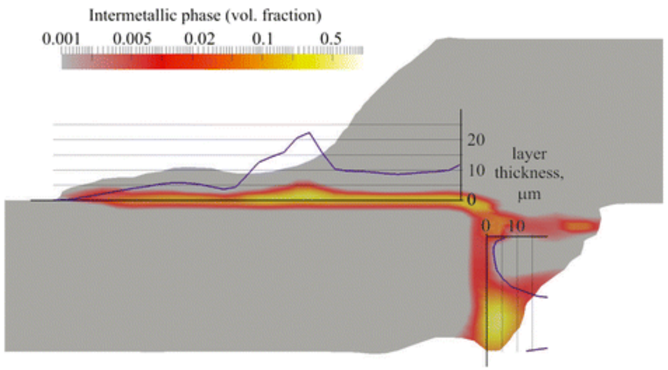


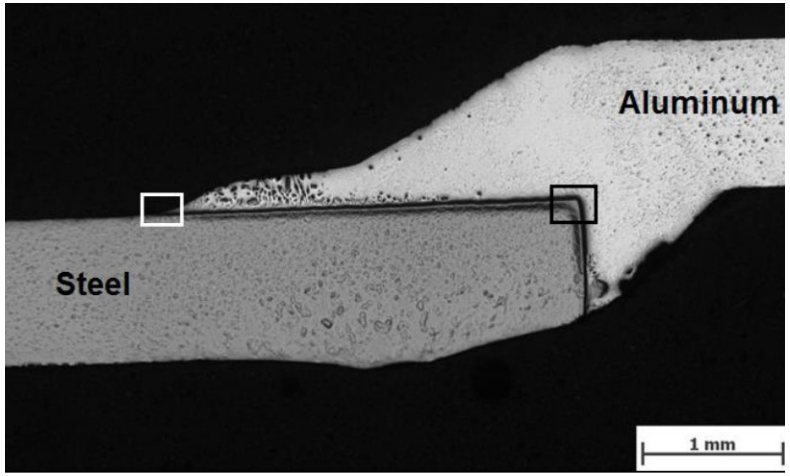


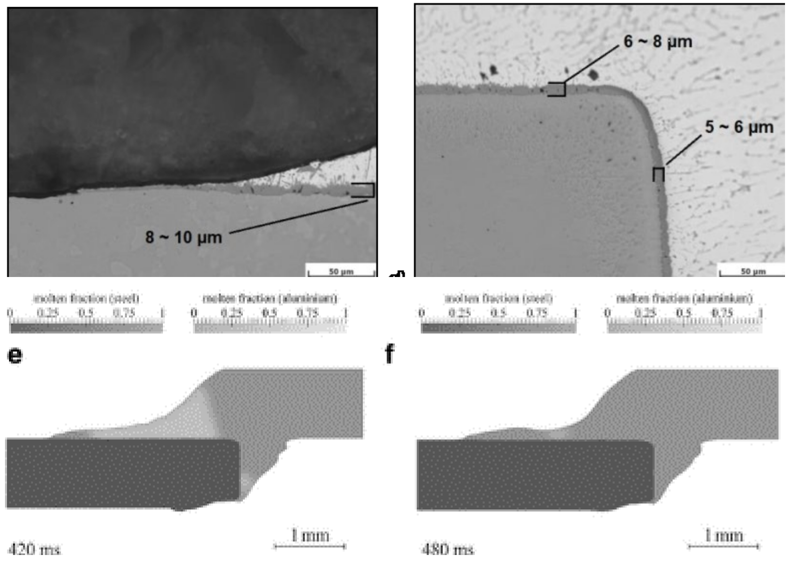
Appl. Surf. Sci. 559 (2021) 149897

Macro processing – joining of dissimilar materials

- Joining of dissimilar materials, like aluminum and steel is challenging due to different material properties and the formation of brittle intermetallic compounds





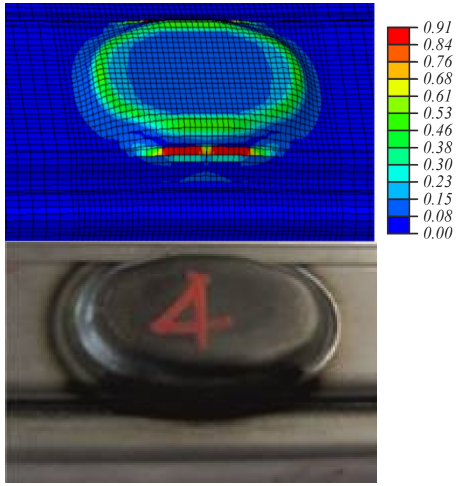


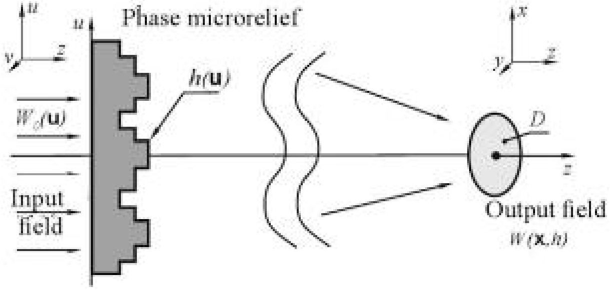
Lasers Manuf. Mater. Process. 5, 1–15 (2018). doi:10.1007/s40516-017-0049-8

- Macro processing – modification of material properties

- Tailor-made laser beam intensity profiles can improve processing quality and selectively change material properties

- Within the framework of a current, multi-year basic research project, funded by the FWF, changes in the local material properties of dual-phase steels illuminated with laser radiation modified by diffractive optical elements are investigated





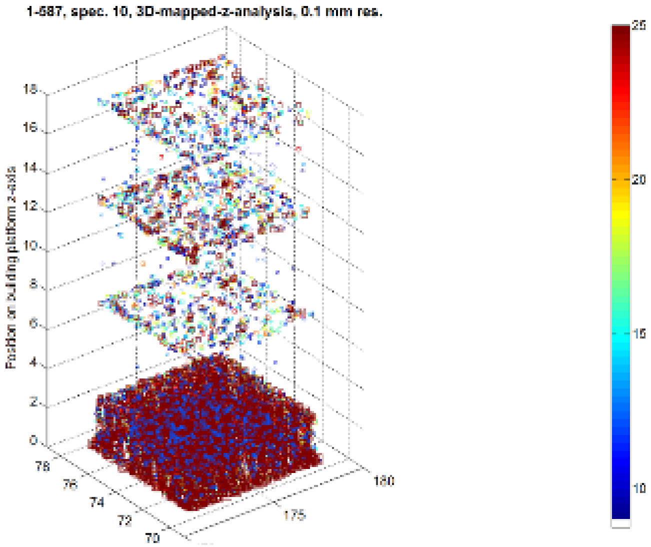
Schematic illustration of a micro-relief for the generation of a homogeneous intensity distribution

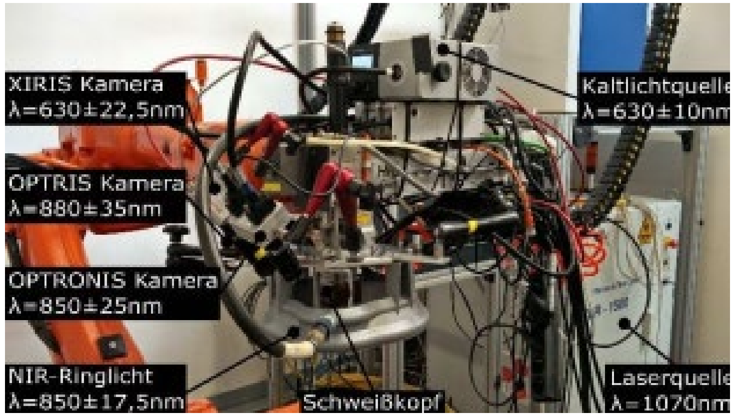
2020 International Conference on Information Technology and Nanotechnology (ITNT), 2020, pp. 1-4

Macro processing – Quality monitoring during additive manufacturing

- Additive manufacturing: Development of a quality monitoring system for powder bed laser fusion processes.

- Within a multi-year research project with partners from the industry, funded by the FFG, different strategies to detect component defects have been investigated. A machine learning approach was able to predict certain defects.



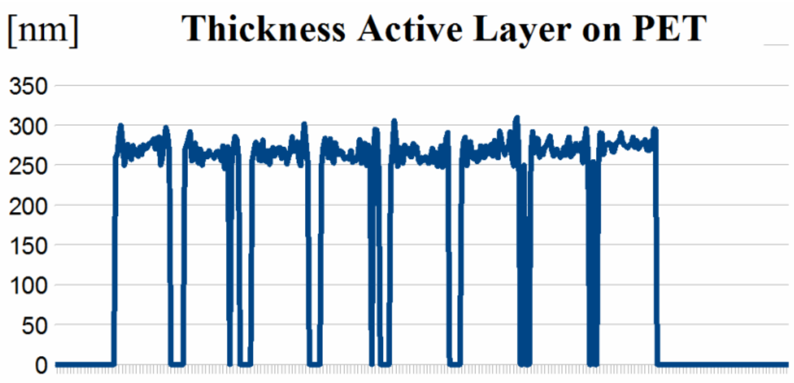


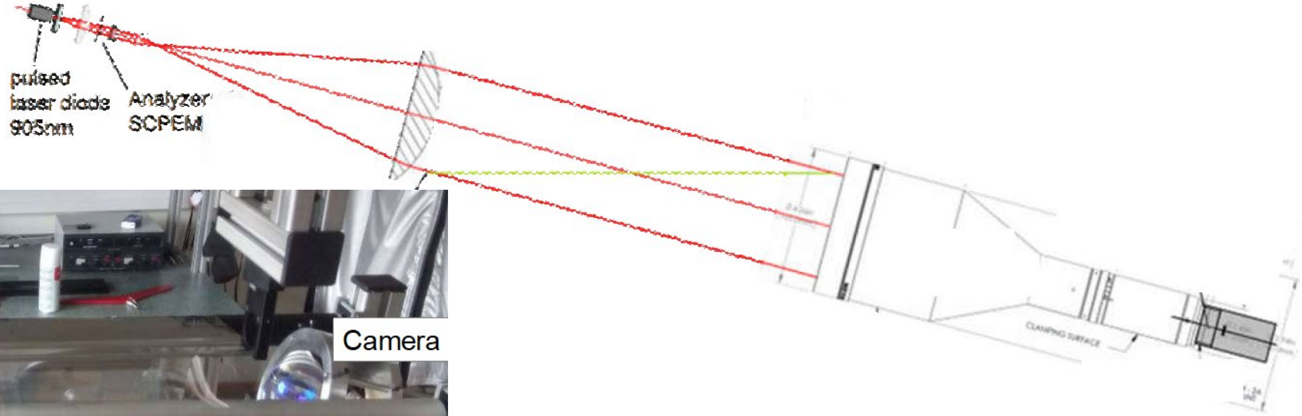
FFG-Project #859775 (Final report:04/2020)

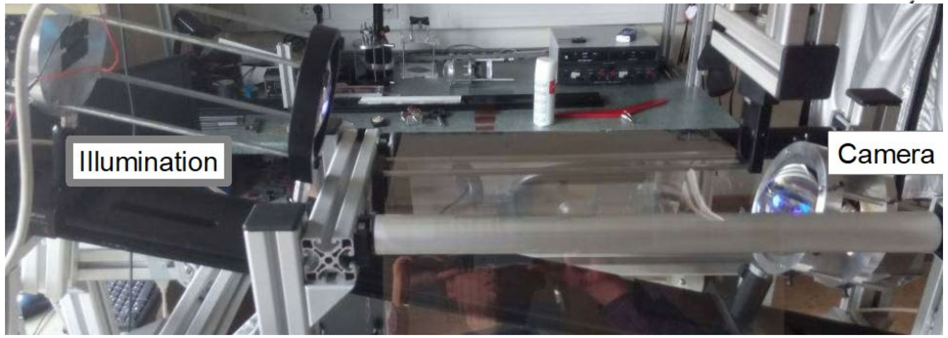
Macro/Micro processing -Thickness measurement by an ellipsometer

- A defined thickness of a layer on substrates is very often quite important for different components, like displays, PV-cells, …

- A fast imaging ellipsometer, based on a SCPEM has been developed to analyze thin film thickness on substrates (range: 10 nm - 2.5 µm, sample size 250 mm)

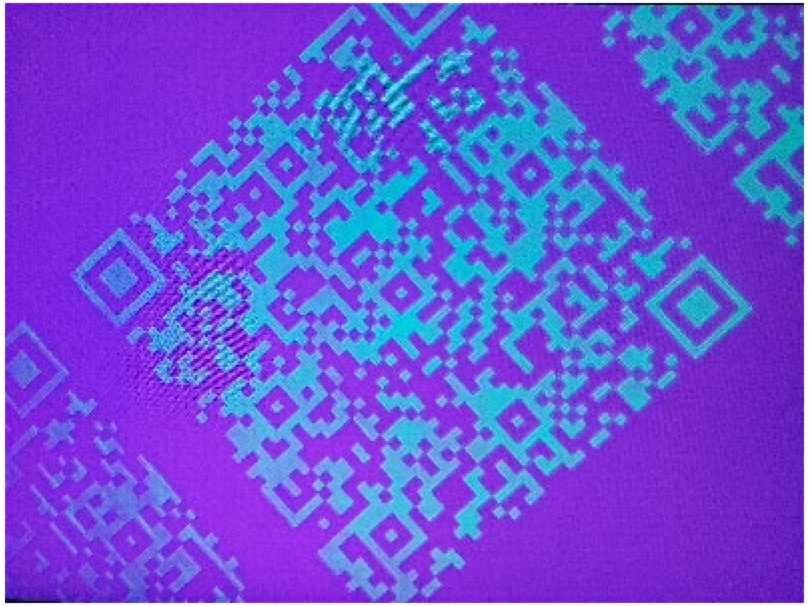






Micro/nano processing – nanostructures for data storage

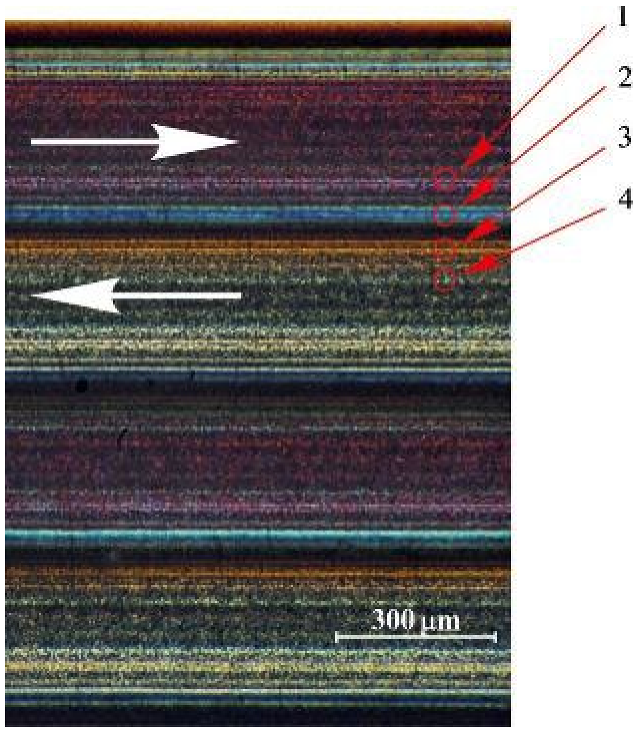
- Long-term data storage is a major problem of our digital age, as current hard disks and solid-state drives have to be replaced regularly to prevent data-loss, for example.
- Writing of nanostructures on ultra-hard ceramic coatings for data storage:
  - Extremely low energy consumption
  - extremely durable and long-lasting
  - Development of fast reading/writing processes

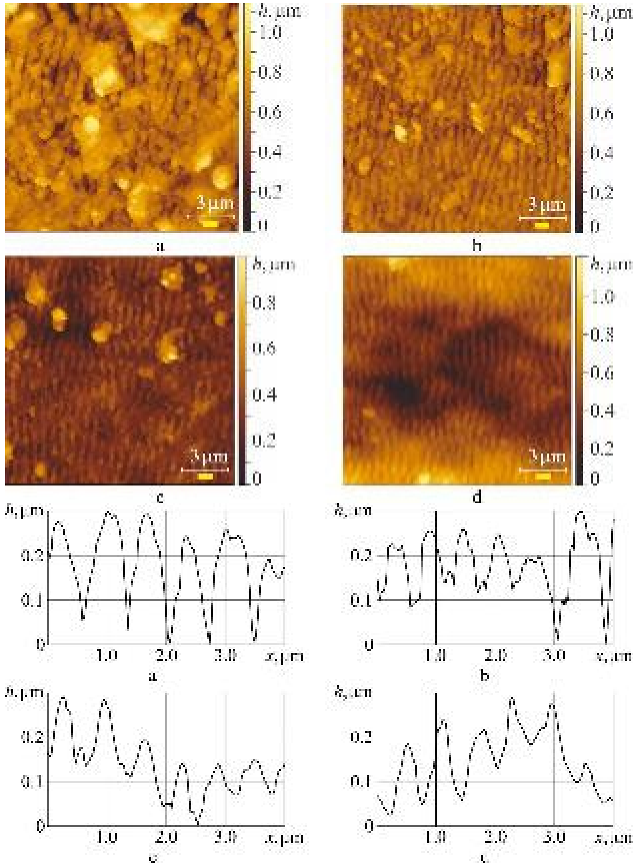


2022 FFG Projekt# 44524216

Nano processing – Modification of the surface color

- Micro- and nanostructuring with an ultrafast laser – color depends on intensity distribution

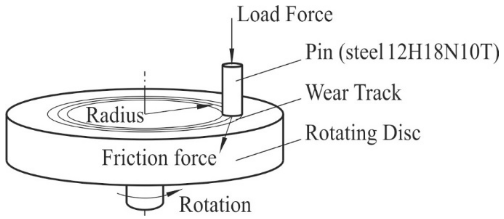


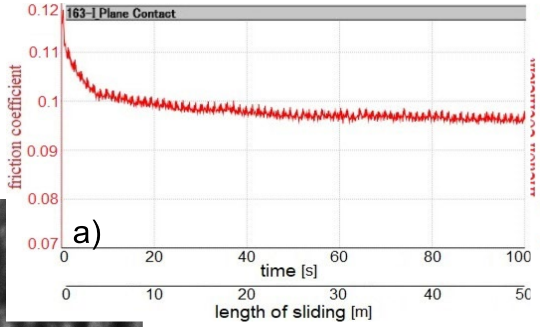


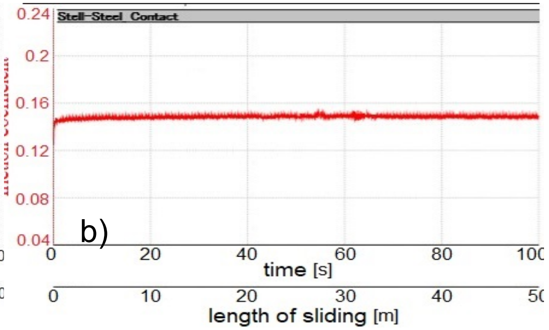
Optics & Laser Technology, Vol 119, Nov. 2019

Nano processing – Modification of tribological properties

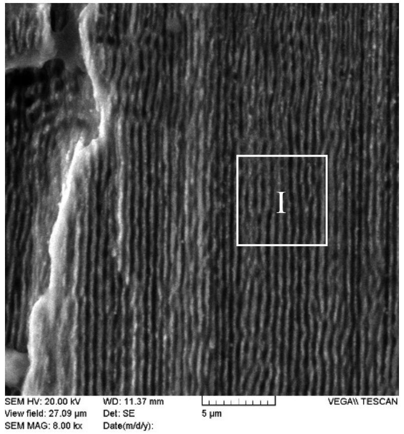
- Steel samples have been laser treated by an ultrafast laser system
- Micro- and nanostructured surfaces were investigated
- Friction coefficient was reduced by ~35%

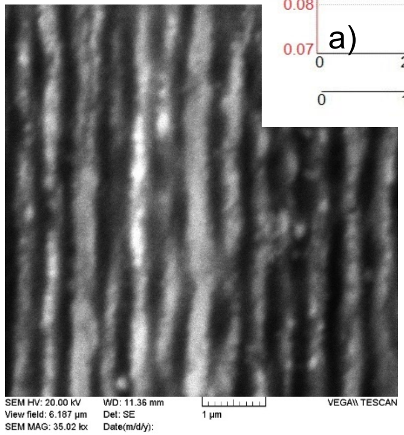






Friction coefficient of steel samples:
a) laser treated sample. b) untreated sample

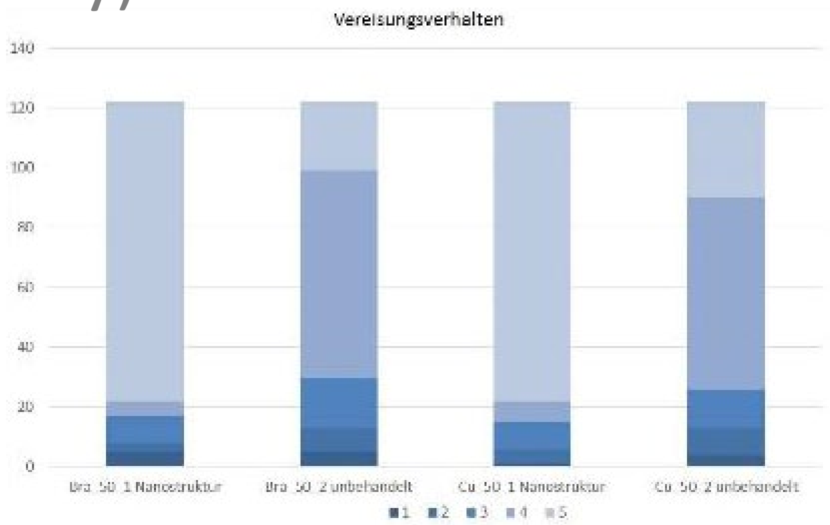




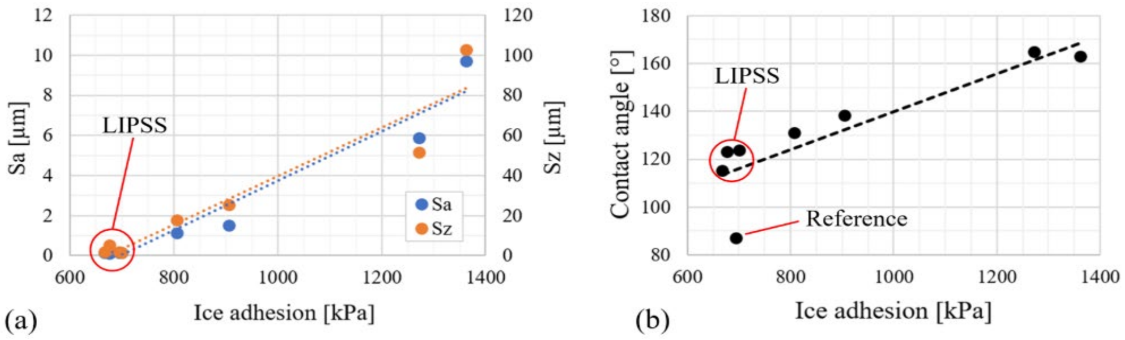
Coatings 2020, 10, 606
doi:10.3390/coatings10070606

Micro & nano processing – Modification of adhesion properties (icephobicity)

- Micro- and nanostructured materials can show hydrophobic and superhydrophobic properties – which can influence ice formation
- Ongoing research projects are devoted towards an investigation of "icephobic" properties of nanostructured surfaces as well as on the adhesion of other liquids on such surfaces

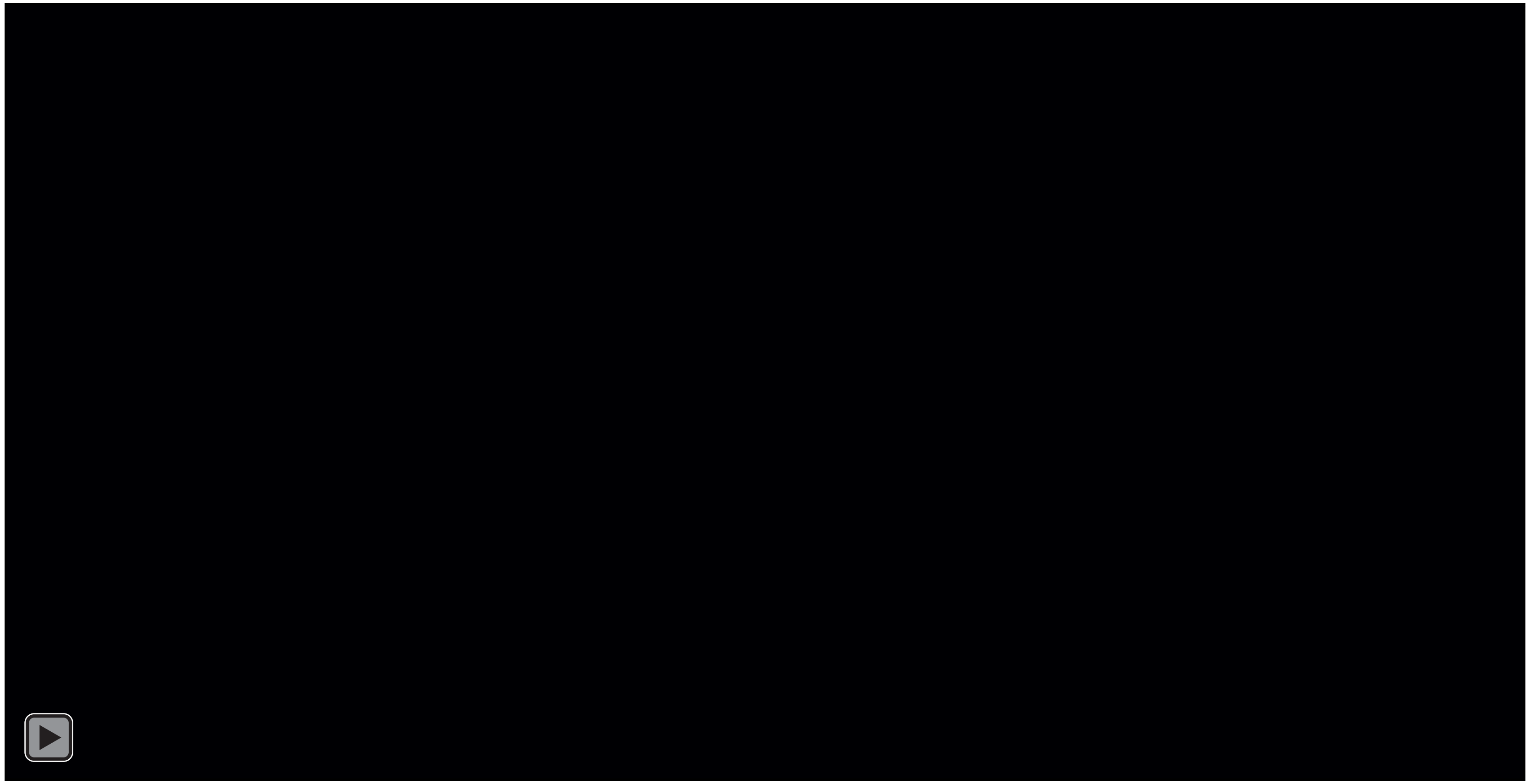


Ice formation on unstructured and nano-structured surfaces (brass, copper). 1 - maximum icing, 5 - no icing.



Proc. SPIE 11674, Laser-based Micro- and Nanoprocessing XV, 1167417 (2021), invited

From laser beam welding…



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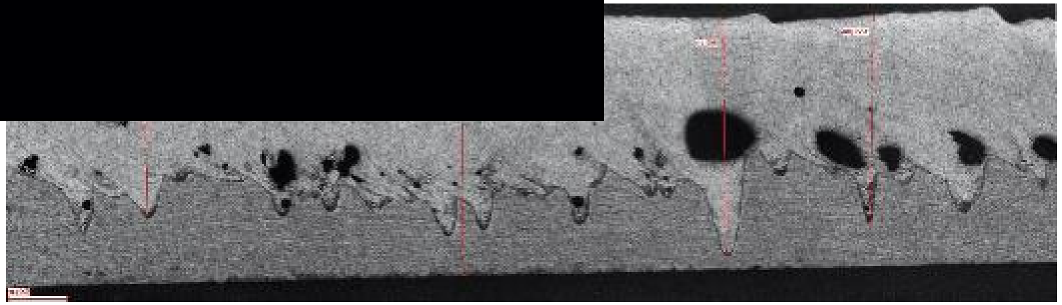
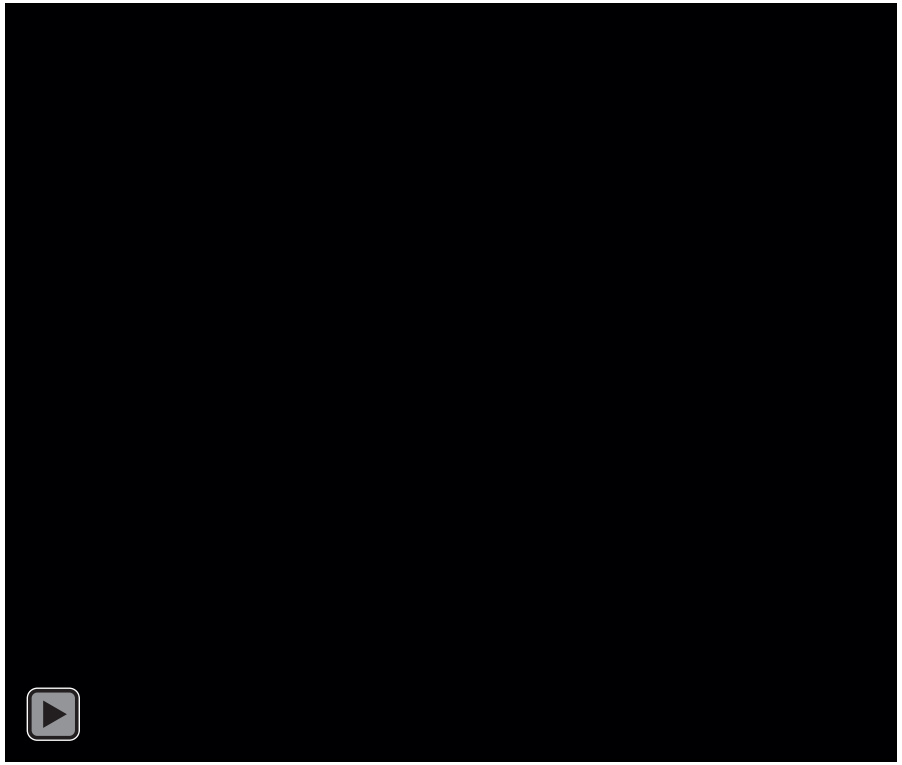
arameter set	A
aterial	Al 99.5
aser power	2 kW
eed rate	10 m/min
ocus diameter	100 µm
ocus position	-2 mm
eam quality M^2	3.82

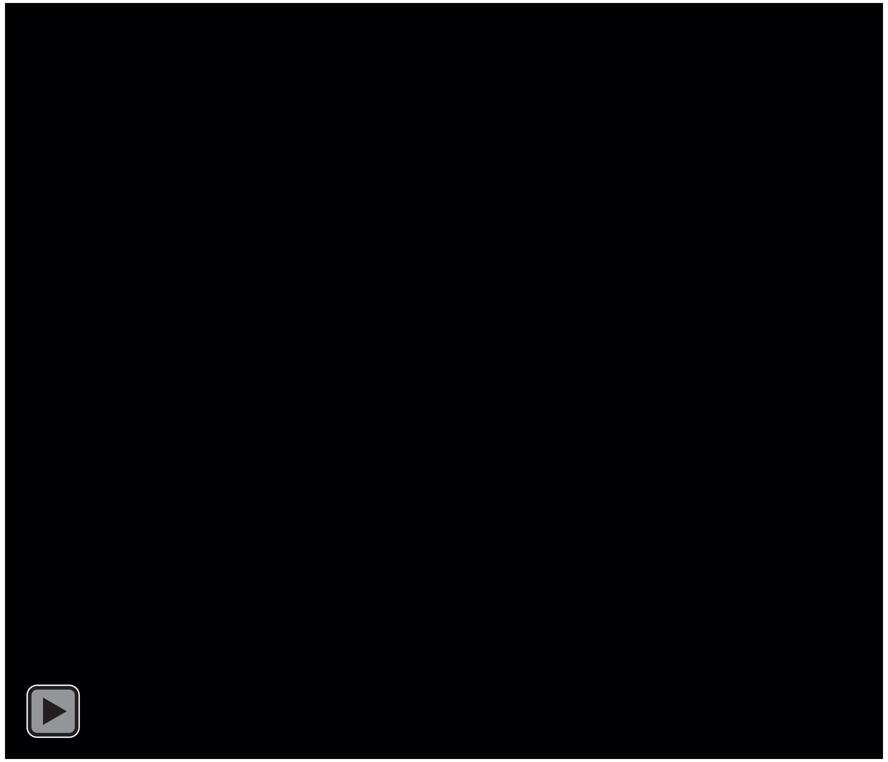


…to ablation with ultra short pulses…

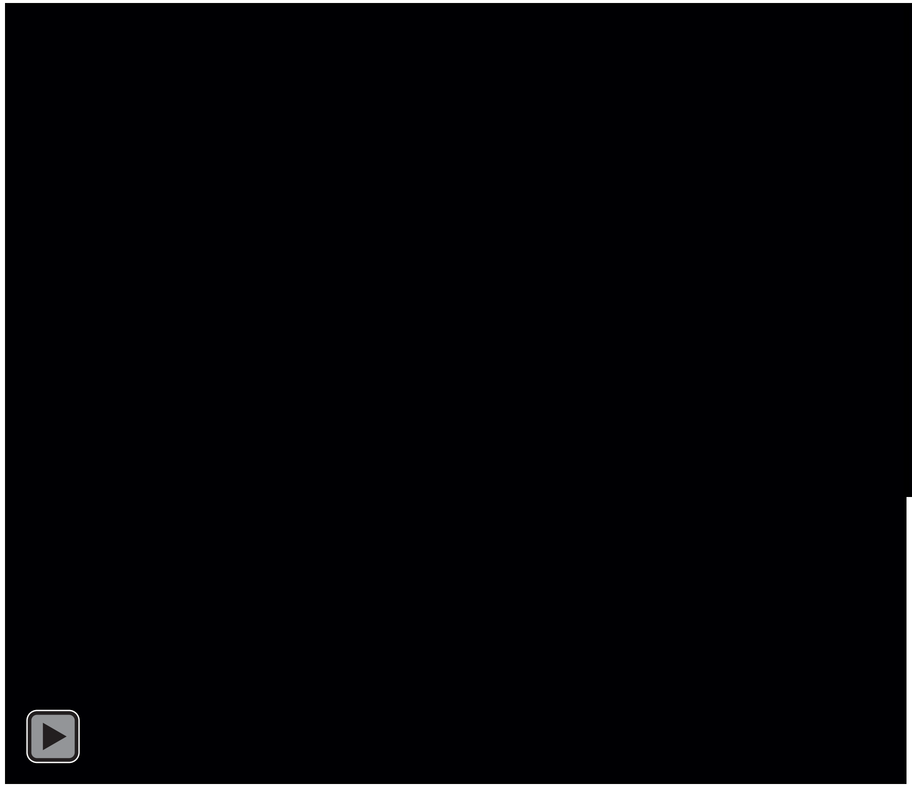
ps pulses



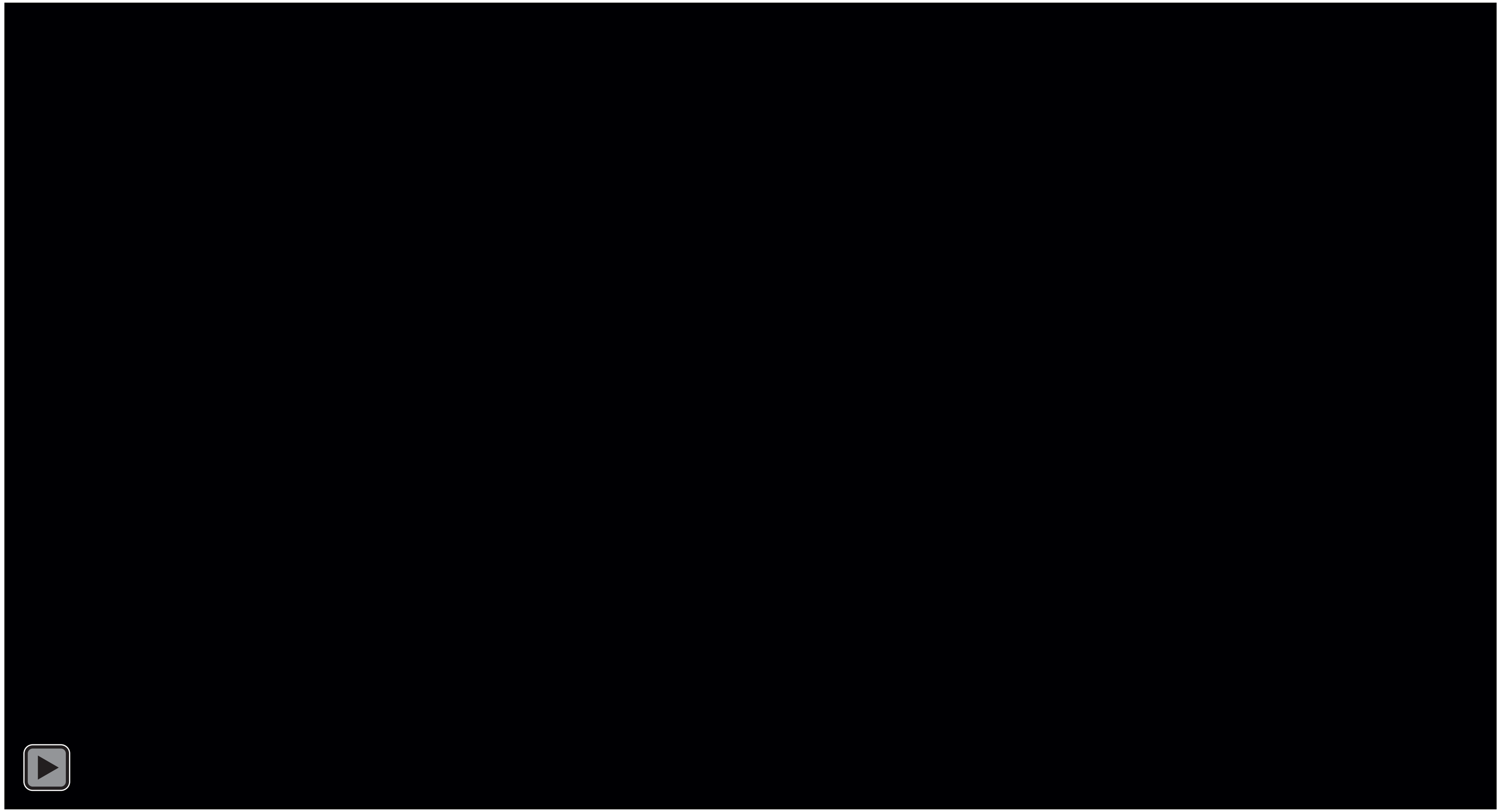
ns pulses



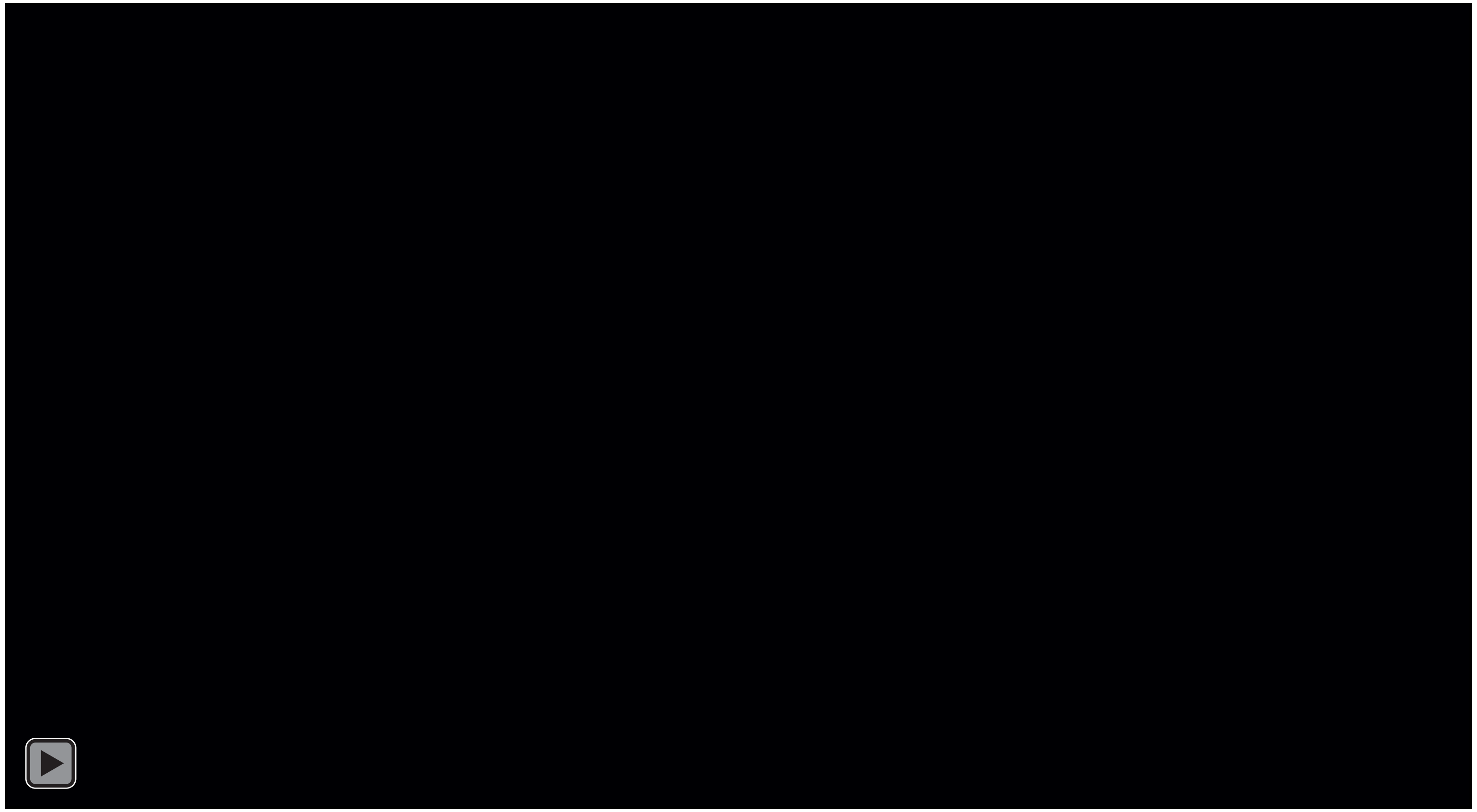
… to laser powder bed fusion



... thermomechanics...



... to a grain growth model



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